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CRACK TOUGHNESS CHARACTERISTICS OF SEVERAL ALLOYS FOR USE IN HEAVY SECTIONS OF HIGH SPEED AIRCRAFT

by Raymond T. Bubsey and William F. Brown, Jr.

Lewis Research Center

Cleveland, Ohio



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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

Plane strain crack toughness K_{Ic} tests were made on four heavy section candidate alloys for high speed aircraft. The data are analyzed by using the plane strain crack-size factor $(K_{Ic}/\sigma_{YS})^2$, where σ_{YS} is the 0.2-percent yield strength. The alloys investigated were maraging 250 grade steel, 9Ni-4Co-30 steel, 300M steel, PH 13-8Mo stainless steel, and titanium 6Al-6V-2Sn. These alloys were supplied in fabricated section sizes which ranged from 1/2-inch (13-mm) plate to 13- by 13-inch (330- by 330-mm) forgings. Single-edge-crack tension specimens were used to study the influence of crack orientation in respect to the fibers and to establish the general influence of section size. Double-edge-crack tension specimens were used to determine the effect of test temperature which varied from -110° F (194 K) to 650° F (617 K). The influence of melting practice on the plane strain crack toughness on maraging 250 grade steel was also investigated.

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SUMMARY

In the selection of high-strength alloys for applications requiring heavy sections, consideration should be given to the crack propagation resistance. This is particularly true for high speed commercial aircraft where weight limitations and safety demand a combination of high strength and toughness. In this investigation, plane strain crack toughness K_{Ic} tests were made on several heavy section candidate alloys for high speed aircraft. The materials selected were maraging 250 grade steel, 9 nickel - 4 cobalt - 30 steel (9Ni-4Co-30), 300M steel, PH 13-8 molybdenum stainless steel (PH 13-8Mo), and a 6 aluminum - 6 vanadium - 2 tin titanium alloy (Ti - 6Al-6V-2Sn). The as-received section sizes ranged from 1/2-inch- (13-mm-) thick plate to 13- by 13-inch (330- by 330-mm) forgings. The investigation included a study of the effects of the following variables on the plane strain crack toughness and on the conventional tensile properties: (1) test temperature between -110° F (194 K) and 650° F (617 K), (2) crack orientation with respect to the fiber, and (3) the as-fabricated section size. In addition, the influence of melting practice was investigated for the maraging steel.

The results are presented in terms of the plane strain crack-size factor $(K_{Ic}/\sigma_{YS})^2$, where σ_{YS} is the 0.2-percent yield strength. All the alloys exhibited a decrease in $(K_{Ic}/\sigma_{YS})^2$ between room temperature and -110° F (194 K). This was particularly pronounced for the PH 13-8Mo steel. For rolled plate or unsymmetrically worked forgings, the anisotropy of fracture properties can be large enough to warrant consideration in design. With the exception of the titanium alloy, the effects of section size on the plane strain crack-size factor were small and not always correlated with relatively large changes in tensile reduction of area. For the titanium alloy, the crack-size factor decreases with decreasing section size, an effect which is associated with the limited hardenability of this alloy compared with the steels. Vacuum-arc remelting appears to improve the fracture properties of 250 grade maraging steel; however, the reason for this improvement could not be tied to a reduction in the residual element content.

It is quite clear from the results of this investigation that a potential improvement in fracture safety of heavy sections should be possible by substitution of maraging 250 grade steel or 6Al-6V-2Sn titanium for 300M steel.

INTRODUCTION

Crack propagation resistance is an important consideration in the selection of structural materials for critical applications. This is particularly true for supersonic aircraft where weight limitations require the use of high strength steel and titanium alloys in heavy sections that are subjected to a wide range of service temperatures. The relative crack propagation resistance of high strength alloys for use in heavy sections is best judged from measurements of the plane strain crack toughness K_{Ic} . The purpose of this investigation was to determine K_{Ic} values for several steels and one titanium alloy that are considered as candidates for use in heavy sections of a supersonic transport airplane. The steels selected were representative of maraging, precipitation hardening, and quenched and tempered types. Variables studied were test temperature (-110° to 650° F or 194 to 617 K), fabricated section size (1/2-in. (13-mm) plate to 13-in. (330-mm) forgings), and crack propagation direction in relation to the fiber. In addition, the effect of melting practice was investigated for the maraging steel. The test temperature range of -110° to 650° F (194 to 617 K) corresponds to that previously selected for investigation of fracture properties in the supersonic transport sheet alloy evaluation program (ref. 1). The upper and lower temperatures of this range extend beyond the operating limits of the proposed commercial aircraft.

Over the past few years, a considerable amount of fracture data for heavy sections has been published and much of this has found its way into the Aerospace Structural Metals Handbook (ref. 2). A program on heavy section properties (ref. 3) was directed specifically to candidate alloys for the supersonic transport airplane. While a considerable amount of this information is useful for defining the general effects of sharp notches or cracks, valid K_{Ic} values cannot be determined from the great majority of the data. This difficulty arises primarily because the procedures for determining (and therefore defining) plane strain fracture toughness were not available to the investigators at the time of the test programs.

Recently the ASTM Committee E-24 on Fracture Testing of Metals has formulated a Recommended Practice (ref. 4) for determining K_{Ic} for high strength alloys by using a notched and fatigue-cracked bend specimen. The basis for development of this standard is given by Srawley, Jones, and Brown (ref. 5), and the general concepts involved in plane strain fracture toughness testing are reviewed in an earlier publication (ref. 6). The present investigation did not employ bend specimens, but double- and single-edge-crack tension specimens. However, the instrumentation and data analysis procedures used in this investigation were the same as those described in the proposed ASTM Recommended Practice. We believe that the values of K_{Ic} obtained would not be different had bend specimens been used. The results from tests which did not meet the requirements for valid K_{Ic} determination are designated as K_Q values. These are not necessarily

equal to K_{Ic} , but in some cases help in establishing curve trends. As described herein, the plane strain crack-size factor $(K_{Ic}/\sigma_{YS})^2$ is used as an index of crack propagation resistance, rather than K_{Ic} alone.

MATERIAL

Four heavy section alloys were selected for the major portion of this program. They were the maraging 250 grade steel, PH 13-8Mo precipitation hardening stainless steel, 9Ni-4Co-30 steel, and the 6Al-6V-2Sn titanium alloy. In addition, a limited number of tests were made on 300M steel, which is considered a representative of steels presently used in commercial aircraft landing gear. The section sizes and forms investigated are listed in table I. For the steels they ranged from 13-inch (330-mm) square forgings to 1/2-inch- (13-mm-) thick cross-rolled plates. The maximum forged section for the 6Al-6V-2Sn titanium was $4\frac{1}{2}$ by $4\frac{1}{2}$ inches (114 by 114 mm) since applications using section sizes appreciably larger than this are severely limited by low hardenability. The $4\frac{1}{2}$ -inch (114-mm) square bar also represents the smallest section from which the crack-toughness specimens could be machined from the bar in all directions.

The chemical composition of each alloy is tabulated in table II. As noted in the table, three heats of maraging 250 grade steel were studied. The air melt and the vacuum-arc remelt were processed from the same 13-ton (13 200-kg) electric furnace heat. One-half of the parent heat was cast into a 26-inch- (66-cm-) diameter ingot and processed as the air melt. The balance was cast into a 21-inch- (53-cm-) diameter electrode and vacuum-arc remelted to a 25-inch- (64-cm-) diameter ingot. The fabrication history for the various products from both heats was essentially the same.

TABLE I. - PRODUCT FORMS AND SECTION SIZES

Alloy	Melting practice	Forgings				Cross-rolled plate	
		Cross-sectional size, in. (mm)					
		13 by 13 (330 by 330)	4½ by 13 (114 by 330)	4½ by 4½ (114 by 114)	1½ by 13 (38 by 330)	1½ by 13 (38 by 330)	½ by 13 (13 by 330)
Maraging 250	Air melt	X	X	X		X	X
Maraging 250	Vacuum-arc remelt	X	X	X		X	X
Maraging 250	Double-vacuum melt	X		X			
9Ni-4Co-30	Vacuum-arc remelt			X			
300M	Vacuum-arc remelt			X			
PH 13-8Mo	Double-vacuum melt	X		X	X		
Ti - 6Al-6V-2Sn	Vacuum-arc melt			X		X	X

TABLE II. - CHEMICAL ANALYSIS

Alloy	Melting practice	Heat number	Composition ^a , wt. %								
			C	Si	Mn	S (b)	P (b)	Mo	Co	Ni	Cr
Maraging 250 ^c	Air melt ^d	Vanadium alloys 35533	0.02	0.06	0.06	0.004 (.0023)	0.004 (.0067)	4.75	7.50	18.23	-----
Maraging 250 ^c	Vacuum-arc remelt ^d	Vanadium alloys 09759	.02	.03	.05	.006 (.003)	.004 (.003)	4.71	7.38	18.20	-----
Maraging 250 ^c	Double-vacuum melt	Carpenter Z80513	.006	.02	.01	.007 (.011)	.003 (.0049)	4.77	7.48	18.41	-----
9Ni-4Co-30	Vacuum-arc remelt	Republic 3930852	.32	.01	.16	.007	.005	.94	4.25	7.62	1.03
300M	Vacuum-arc remelt	Republic 3931497	.41	1.77	.81	.003	.007	.40	----	1.85	.83
PH 13-8Mo	Double-vacuum melt	Armco VC5281	.042	.02	.02	.004	.003	2.06	----	8.07	12.58
Ti - 6Al-6V-2Sn	Vacuum-arc melt	TMCA D7883	.025	----	----	-----	-----	----	----	-----	-----

Alloy	Melting practice	Heat number	Composition ^a , wt. %							
			Ti	Al	Sn	V	Fe	O ₂ (b)	N ₂ (b)	Other
Maraging 250 ^c	Air melt ^d	Vanadium alloys 35533	0.40	0.13	---	----	Bal.	(0.0059)	(0.0099)	B, 0.0025 Zr, 0.014 Ca, 0.05
Maraging 250 ^c	Vacuum-arc remelt ^d	Vanadium alloys 09759	.42	.14	---	----		(.0021)	(.0113)	B, 0.003 Zr, 0.016 Ca, 0.05
Maraging 250 ^c	Double-vacuum melt	Carpenter Z80513	.42	.14	---	----		(.0035)	(.0106)	B, 0.001
9Ni-4Co-30	Vacuum-arc remelt	Republic 3930852	----	----	---	0.08		-----	-----	-----
300M	Vacuum-arc remelt	Republic 3931497	----	----	---	.08		-----	-----	-----
Ph 13-8Mo	Double-vacuum melt	Armco VC5281	----	1.11	---	----		-----	-----	-----
Ti - 6Al-6V-2Sn	Vacuum-arc melt	TMCA D7883	Bal.	5.5	1.9	5.4	0.65	0.12	0.012	H ₂ , 0.005 Cu, 0.64

^aComposition according to supplier.^bValues in parenthesis determined from specimens.^cASTM A 538-65 gives the following maximum values: C, 0.03; Si, 0.10; Mn, 0.10; S, 0.10; and P, 0.010.^dFrom same parent heat.

The double-vacuum melt was made by using special practices designed to give low residual element content. An induction-vacuum melt (vacuum alloyed) was cast into an electrode and vacuum-arc remelted to a 20-inch- (51-cm-) diameter ingot. The finished forgings and plates for all three heats of maraging steel were solution annealed by the supplier at 1500⁰ F (1089 K) and air cooled.

The 4 $\frac{1}{2}$ -inch (114-mm) square forging of 9Ni-4Co-30 steel was processed from a vacuum-arc remelt. Deoxidation was accomplished with carbon during the vacuum remelting. This steel was received in the annealed condition.

The 300M steel was obtained from vacuum-arc-remelted stock intended for aircraft landing gear application and was received in the annealed condition.

The PH 13-8Mo stainless steel was vacuum-induction melted and then vacuum-arc remelted. The final forgings were solution treated by the supplier at 1700⁰ F (1200 K) and air cooled.

The 6Al-6V-2Sn titanium heat was double melted by vacuum-arc techniques to a 26-inch- (66-cm-) diameter ingot. Part of this heat was broken down to a 4 $\frac{1}{2}$ -inch- (114-mm-) square forging which was annealed at 1300⁰ F (978 K) for 2 hours. This annealed forging was then solution treated for 1 hour at 1650⁰ F (1173 K) and water quenched. The material for the plate products was forged to a 3- by 12-inch (76- by 305-mm) slab that was cross rolled to the 1 $\frac{1}{2}$ -inch- (38-mm-) and $\frac{1}{2}$ -inch- (13-mm-) thick plates. The rolled plates were annealed at 1350⁰ F (1005 K) for 8 hours and furnace cooled, and then solution treated at 1550⁰ F (1116 K) for 15 minutes at temperature and water quenched. These heat treatments were performed by the supplier.

PRELIMINARY TESTS AND HEAT TREATMENTS

In general, the alloys were given the heat treatments recommended by the manufacturer, and these are summarized in table III which shows the heat treatment and machining sequence. Where possible, solution treating or austenitizing was carried out in the full final section size to develop center properties typical of those in heavy section service components. As mentioned in the previous section, all alloys except 300M and 9Ni-4Co-30 steel were austenitized or solution treated in full section size by the supplier. These two alloys were completely heat treated by the investigators, as described in the following section.

Aging or tempering was carried out in a forced-air electric furnace prior to fatigue cracking. The specimens were suspended from a cross bar and separated by spacers to ensure a free flow of heated air around each specimen. The temperature was monitored by a thermocouple inserted between the specimens. Prior to heat treating, the specimens were scrubbed with acetone and wiped clean.

TABLE III. - HEAT TREATMENT

Alloy	Heat treatment for forging or plate	Heat treatment for specimens ^a
Maraging 250 (all heats)	1500 ^o F (1090 K) for 1 hr; air cooled	Aged at 950 ^o F (783 K) for 3 hr; air cooled
9Ni-4Co-30	1125 ^o F (880 K) for 16 hr; air cooled	1700 ^o F (1200 K) for 1 hr; air cooled 1550 ^o F (1115 K) for 1/2 hr; salt quenched to 460 ^o F (512 K); hold for 7 hr; tempered at 1000 ^o F (811 K) for 2 hr; air cooled
300M	1700 ^o F (1200 K) for 3½ hr; air cooled; 1600 ^o F (1145 K) for 1½ hr; salt quenched to 1000 ^o F (811 K); hold for 1 hr; oil quenched at 110 ^o F (317 K); hold for 1/2 hr; tempered at 575 ^o F (575 K) 2 + 2 hr; air cooled	None
PH 13-8Mo	1700 ^o F (1200 K) for 1 hr; air cooled; -110 ^o F (194 K) for 16 hr	1000 ^o F (811 K) for 4 hr; air cooled
Ti - 6Al-6V-2Sn	Plate: 1550 ^o F (1115 K) for 15 min; water quenched Forging: 1650 ^o (1170 K) for 1 hr; water quenched	1050 ^o F (839 K) for 4 hr; air cooled

^aFatigue cracked after heat treatment.

Maraging 250 Grade Steel

It is desirable to compare melting practices by heat treating material from each heat to the same strength level. Therefore, an investigation was made to determine the aging response of the three maraging steel heats. Transverse smooth specimens were machined from the 4½-inch- (114-mm-) square forgings at mid-radius positions, aged for three hours at 850^o, 900^o, 950^o, and 1000^o F (728, 755, 783, and 811 K) and tensile tested at -110^o F (194 K). The results shown in figure 1 indicate quite uniform response to the aging treatments. However, there is a spread in the yield strength at the lower aging temperatures. The double-vacuum melt exhibits a lower reduction in area than either the air melt or vacuum-arc remelt. The maximum strength occurred near 950^o F (783 K) and overaging was evident at 1000^o F (811 K). On the basis of these results, a 950^o F (783 K), 3-hour age was applied to specimens for all three heats.

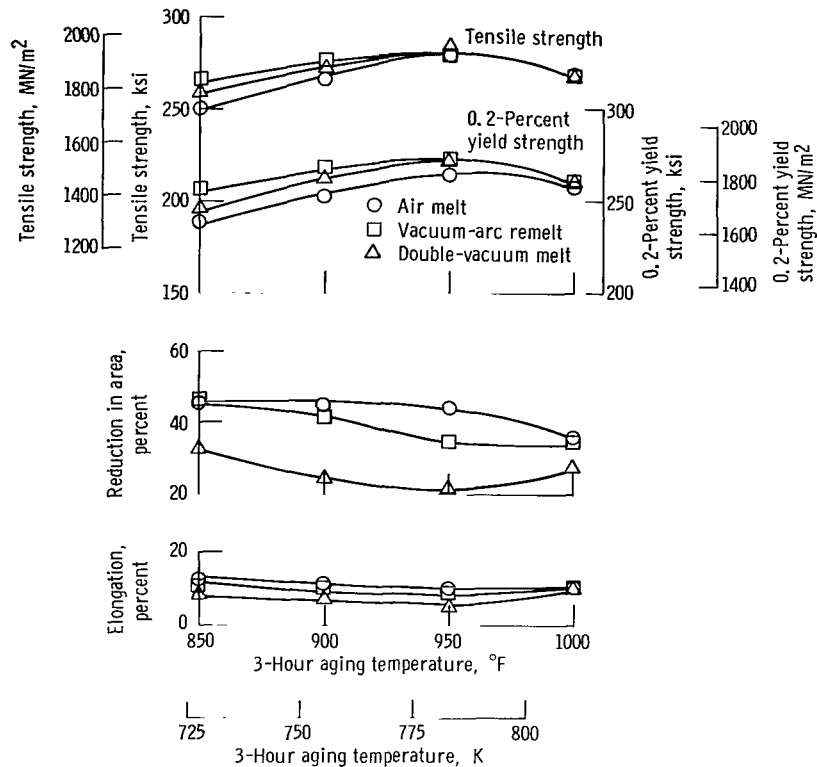


Figure 1. - Effect of aging temperature on
 -110° F (194 K) transverse smooth tensile
 properties of three heats of $4\frac{1}{2}$ - by $4\frac{1}{2}$ -inch
 (114- by 114-mm) maraging 250 steel.
 (1500° F (1200 K) for 1 hr, air cooled; aged
 3 hr, air cooled.)

9Ni-4Co-30 Steel

An isothermal heat treatment was used to produce a lower bainite which was then tempered. Because of difficulty in machining the bainite, a study was made to determine whether the tensile properties would be different if machined specimens were quenched rather than the full forged section. The hardenability of the alloy was checked by quenching and tempering a 12-inch (305-mm) length of the $4\frac{1}{2}$ - by $4\frac{1}{2}$ -inch (114- by 114-mm) forging which was then cut into tensile specimens representing different positions through the thickness of the forging. The results are shown in table IV which also gives tensile data for specimens completely heat treated after final machining. The center strength properties are only slightly lower than those of the surface or of the specimens machined prior to heat-treating. On the basis of these results it was judged feasible to heat treat

TABLE IV. - HEAT TREATMENT RESPONSE OF 9Ni-4Co-30 STEEL

4 $\frac{1}{2}$ - BY 4 $\frac{1}{2}$ -INCH (114- BY 114-MM) FORGING

[Average of two tests at each location.]

Location in forging	Section heat treated	Room temperature tensile properties					
		0.2-Percent yield strength		Tensile strength		Elongation, percent	Reduction in area, percent
		ksi	MN/m ²	ksi	MN/m ²		
Surface	Full	198	1365	226	1558	16	52
Center	Full	192	1324	221	1524	17	52
Mid-radius	Specimen	197	1358	228	1572	19	56

specimens fully after final machining. A normalizing treatment was conducted in an argon atmosphere and austenitizing was performed in a salt bath.

300M Steel

The 4 $\frac{1}{2}$ - by 4 $\frac{1}{2}$ -inch (114- by 114-mm) forging was completely heat treated in full section by the investigators. The heat treatment employed is typical of that used for large aircraft landing gear components. The step cooling from the austenitizing temperature is designed to minimize thermal stresses and distortion during quenching. This treatment results in a few percent (2 to 5 percent) of acicular bainite at the center of a 4 $\frac{1}{2}$ - by 4 $\frac{1}{2}$ -inch (114- by 114-mm) forging.

PH 13-8Mo Steel

It was necessary to resolution treat the 4 $\frac{1}{2}$ - by 4 $\frac{1}{2}$ - inch (114- by 114-mm) forging because a previous treatment by the supplier, inadvertently applied, resulted in excessive amounts of retained austenite. To minimize the amount of retained austenite, all forms of this alloy were refrigerated at -110⁰ F (194 K) before aging. The necessity for this cold treatment will depend on small compositional variations within the specified range which can result in an Ms below room temperature. Specimens were aged at 1000⁰ F (811 K) for 4 hours in air.

Ti - 6Al-6V-2Sn

Specimens from the solution-treated products were aged at 1050⁰ F (839 K) for 4 hours in air. This treatment is sometimes known as a duplex anneal. It is designed to provide higher tensile strength than the conventional anneal and still retain adequate ductility.

SPECIMENS

Four types of crack toughness specimens were employed (fig. 2). For most of the

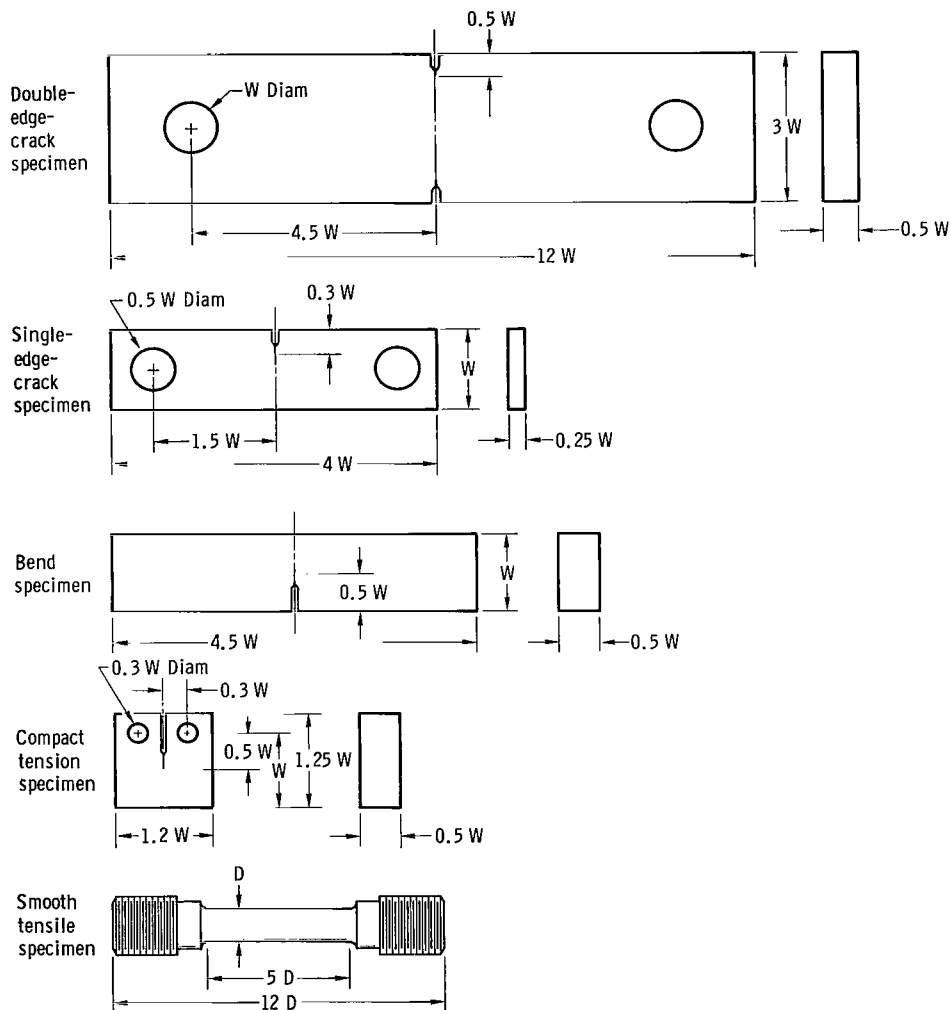


Figure 2. - Crack toughness specimens. $W = 1.0$ inch (25.4 mm); $D = 0.25$ inch (6.35 mm).

testing 1/4-inch- (6.4-mm-) thick single-edge-crack tension specimens and 1/2-inch- (13-mm-) thick double-edge-crack tension specimens were used. Based on the ASTM specimen size requirements (refs. 5 and 6), the K_{IC} measurement capacity of these specimens is $0.32 \sigma_{YS}$ and $0.45 \sigma_{YS}$, respectively. The double-edge-crack specimen was used to determine the conventional crack (notch) strength as well as K_{IC} values. Tests in the short transverse direction of the plate products required the use of a compact tension (crack line loaded) specimen (ref. 6). The K_{IC} values from the compact tension specimen agreed well with those obtained from the single-edge-crack specimen, as indicated in table VII for tests on the titanium alloy. The 300M steel was evaluated by using bend specimens produced in accordance with the recently formulated ASTM Recommended Practice (ref. 4). Both the compact tension and the bend specimens were 1/2 inch (13 mm) thick and had the same K_{IC} measurement capacity as the double-edge-crack specimens.

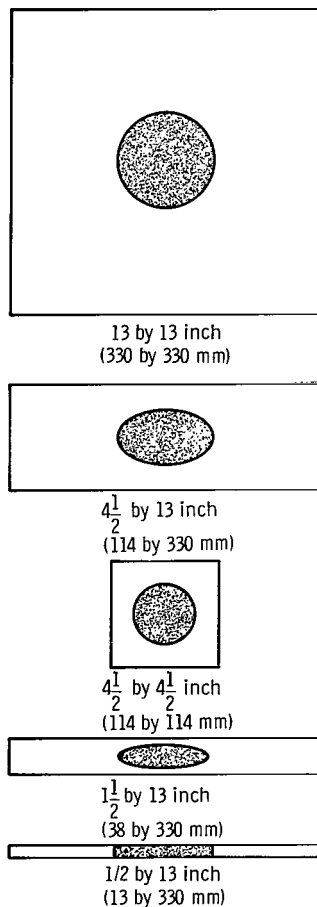


Figure 3.- Cross sections of various forms investigated showing regions which contained crack tips of crack toughness specimens.

All the crack toughness specimens were cut from the central section of each forging or plate because this region was expected to possess the poorest toughness. The shaded areas in figure 3 represent the regions containing the specimen crack tips. The smooth specimens were taken from mid-radius positions for the square cross sections and at the one-quarter width positions for the rectangular cross sections. Smooth tensile properties were obtained, where possible, in the three conventional testing directions; longitudinal, transverse, and short transverse.

Six orientations were investigated using single-edge-crack specimens, as shown in figure 4. The ASTM (ref. 7) notation is used to identify the various crack orientations studied. The first letter represents the direction of the normal to the crack plane, and the second letter the direction of crack propagation: W is intended to denote the width direction, R the rolling (or forging) direction, and T the thickness direction. In the square cross-section forgings, the W and T directions presumably are identical and were established arbitrarily by color coding one side of the forgings. The TW4 orientation was at 45° to a surface. Single-edge-crack tension specimens in the RT, RW, WR, WT, TW, and TW4 orientations were machined from the 13- by 13-inch (330- by 330-mm), $4\frac{1}{2}$ - by $4\frac{1}{2}$ -inch (114- by 114-mm), and $4\frac{1}{2}$ - by 13-inch (114- by 330-mm) forgings. Compact tension specimens were used to investigate the TW direction in the $1\frac{1}{2}$ - by 13-inch (38- by 330-mm) plates. Because of thickness limitations, only the RW and WR orientations could be tested in the $\frac{1}{2}$ -inch- (13-mm-) thick plates. Single-edge-crack specimens were used for these tests. Double-edge-crack specimens were, in all cases, taken from the $4\frac{1}{2}$ - by $4\frac{1}{2}$ -inch (114- by 114-mm) forgings in the RW orientation with the specimen centerline approximately at the center of the thickness of the plate or forging.

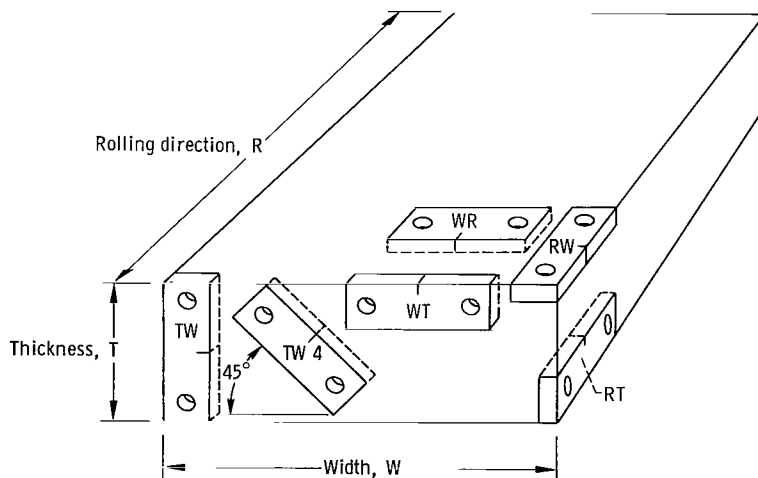
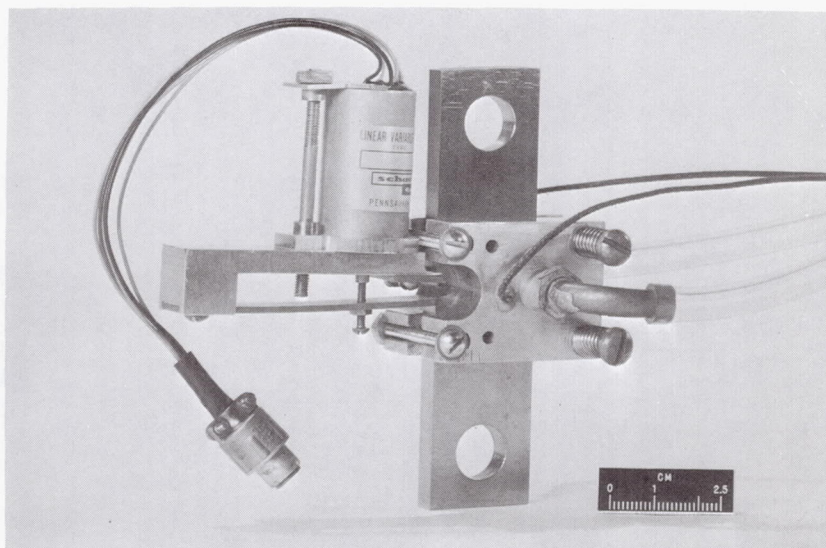


Figure 4. - Schematic drawing of crack orientations investigated by using single-edge-crack specimens. (See fig. 3 for location of cracks with respect to product form cross section.)

Specimen blanks were machined to the configurations shown in figure 2 by using the heat treating and machining sequence given in table III. A chevron-type crack starter notch was used, and the specimens were fatigue cracked in the fully heat-treated condition. All specimens except the compact tension type were fatigue cracked in cantilever bending. The compact tension specimens were cracked in tension-tension. Fatigue cracking procedures were those recommended by ASTM (ref. 4) to ensure adequately sharp cracks.

PROCEDURE

The major portion of the fracture testing was at -110° F (194 K) using the single-edge-crack tension specimen. This temperature is somewhat below the lowest expected to be encountered in aircraft operation. The $1/2$ -inch- (13-mm-) double-edge-crack specimen was used to test the $4\frac{1}{2}$ - by $4\frac{1}{2}$ -inch (114- by 114-mm) forgings in the RW direction at temperatures between -110° F (194 K) and 650° F (617 K). The test procedure was simplified by using cooling plates rather than a liquid bath to chill the specimens. (These plates contained integral passages that were fed cold nitrogen gas from an external heat exchanger.) The method of attaching these cooling plates is illustrated in figure 5, which shows the plates fixed to the single-edge-crack specimen with a displacement gage in place. Tests at temperatures above room temperature were run in a conventional resistance-heated tube furnace. Specimen temperature was monitored by thermocouples on each side of the specimen about $1/4$ inch (6.4 mm) above the crack tip.



C-68-1775

Figure 5. - Cooling plates on single-edge-crack specimen with displacement gage in place.

The experimental procedures used for testing the crack toughness specimens were essentially those given in the ASTM Recommended Practice for Plane Strain Fracture Toughness Testing (refs. 4 and 5). The double cantilever clip-on displacement gage described in the ASTM Recommended Practice uses resistance strain gages on the cantilever arms as displacement sensing transducers. This type of gage is not well suited to low temperature tests of the type used in this investigation where cold gas impinges on the strain gage elements and gives rise to noise in the load-displacement records. Similar problems would be encountered in a low temperature bath where liquid boiling on the arms would result in a noisy signal. Therefore, a modification of this gage was developed (fig. 5) which utilizes a linear variable differential transformer as a displacement sensing transducer. The core of the transformer is attached to a single cantilever beam in such a way that movement of the beam produces displacement of the core. The linearity and measuring range of this gage are essentially equal to that of the double cantilever beam clip-on gage. The linear differential transformer is powered by a carrier amplifier demodulator which also supplies a direct-current output suitable for driving a plotter. During a crack toughness test, output from the displacement gage and from a load cell were fed to a plotter which produced a load-displacement record. Double-edge-crack specimens were provided with a displacement gage for both cracks with the outputs recorded individually against load.

The load-displacement records were analyzed by the procedures outlined by ASTM Recommended Practice (ref. 4). Stress intensity factors were computed from the load and original crack lengths by using the stress analyses given by Brown and Srawley (ref. 6) for the various specimens shown in figure 2. If the test did not yield a valid value of plane strain fracture toughness, a K_Q value is reported corresponding to the load at 2-percent crack extension. The conventional crack strength (maximum load divided by original uncracked area) is also given for the double-edge-crack specimen.

RESULTS AND DISCUSSION

The effects of test temperature, specimen orientation, and section size on the smooth tensile and crack toughness characteristics of the various alloys are considered.

The plane strain crack-size factor $(K_{IC}/\sigma_{YS})^2$, where σ_{YS} is the 0.2-percent yield strength, is used as an index of plane strain crack propagation resistance under conditions of small-scale yielding. It is a more meaningful characteristic of the material than the K_{IC} value alone. The greater the value of $(K_{IC}/\sigma_{YS})^2$, the larger the crack that can be tolerated when a material is stressed to some fraction of its yield strength. Furthermore, the thickness necessary to produce plane strain fracture conditions increases in proportion to this factor. In cases where the test results did not meet all the require-

ments for a valid K_{IC} determination, the ratio of $(K_Q/\sigma_{YS})^2$ is reported. However, average values given in the tables are based only on valid data. For tests with double-edge-crack tension specimens, the ratio between the crack strength and the tensile yield strength (crack-strength ratio) is also given. This ratio, which is based on the maximum load, is a useful index of plane strain crack propagation resistance provided that the failure at maximum load is primarily controlled by a plane strain fracture process. Otherwise, variations in the ratio below 1 are related to crack propagation resistance under mixed-mode conditions. The relation, if any, between mixed-mode fracture toughness and K_{IC} has not been established.

Smooth Tensile Properties

The smooth tensile properties at room temperature and -110° F (194 K) are given in table V for the various product forms tested in the longitudinal, transverse, and short transverse directions. These results apply to the mid-radius position for square cross sections and to the one-quarter width position for the rectangular cross sections. They show the expected higher strength at -110° F (194 K) than at room temperature but no consistent influence of test temperature on elongation or reduction in area for any of the alloys.

Effects of testing direction are noticed only for the elongation and reduction in area for the maraging steels. These values are considerably lower in the transverse or short transverse direction than in the longitudinal direction. This anisotropy is particularly pronounced for the 13-inch (330-mm) sections of the air melt and double-vacuum melt steel.

Additional smooth tensile tests in the longitudinal and transverse directions were made on the $4\frac{1}{2}$ - by $4\frac{1}{2}$ -inch (114- by 114-mm) forging for each alloy to cover the temperature range between room temperature and 650° F (617 K). These data are presented in the next section.

The variation in transverse tensile properties with position relative to the center of the 13- by 13-inch (330- by 330-mm) steel forgings is shown in table VI, along with similar data for the $4\frac{1}{2}$ - by $4\frac{1}{2}$ -inch (114- by 114-mm) forging of Ti - 6Al-6V-2Sn. The steels exhibited little change in the yield strength or tensile strength with position. The air-melted maraging 250 grade steel showed a considerably higher elongation and reduction in area at the edge than at the mid-radius or center of the forging. In contrast, there was essentially no effect of position on ductility of the vacuum-melted heats. The titanium forging showed lower strength at the center than at the surface or mid-radius. This lower strength results from the expected effect of section size on the aging response.

TABLE V. - SMOOTH TENSILE PROPERTIES FOR VARIOUS PRODUCT FORMS

[Average of two tests.]

Alloy	Melting practice	Cross-sectional size		Form	Condition	Test temperature		Test direction	0.2-Percent yield strength		Tensile strength		Elongation, percent	Reduction in area, percent	
		in.	mm			°F	K		(a)	ksi		MN/m ²			
								ksi		MN/m ²	ksi	MN/m ²			
Maraging 250	Air melt	13 by 13	330 by 330	Forging	Aged at 950° F (783 K) for 3 hr	Room	Room	T	230	1586	242	1668	2	5	
								ST	233	1606	246	1696	3	6	
								L	233	1606	247	1703	8	27	
		-110	194	T	251	1730	263	1813	3	6					
				ST	255	1758	270	1862	3	5					
				L	256	1765	271	1868	5	16					
		4½ by 13	114 by 330	Forging	Aged at 950° F (783 K) for 3 hr	Room	Room	ST	240	1655	252	1737	4	7	
								L	239	1648	248	1710	10	47	
								-110	194	ST	264	1820	276	1903	3
		L	260	1793	271	1868	11			48					
		4½ by 4½	114 by 114	Forging	Aged at 950° F (783 K) for 3 hr	Room	Room			T	241	1662	251	1730	10
								L	240	1655	253	1744	13	49	
								-110	194	T	268	1848	278	1917	10
		L	263	1813	275	1896	10			48					
		1½ by 13	38 by 330	Rolled plate	Aged at 950° F (783 K) for 3 hr	Room	Room			T	245	1689	257	1772	10
								L	247	1703	255	1758	9	43	
								-110	194	T	268	1848	281	1937	10
		L	268	1848	279	1924	9			39					
		1/2 by 13	13 by 330	Rolled plate	Aged at 950° F (783 K) for 3 hr	Room	Room			T	250	1724	254	1751	11
								L	253	1744	260	1793	11	56	
								-110	194	T	272	1875	286	1972	11
		L	274	1889	283	1951	10			49					
		Vacuum-arc remelt	13 by 13	330 by 330	Forging	Aged at 950° F (783 K) for 3 hr	Room			Room	T	242	1668	253	1744
								ST	239		1648	250	1724	9	38
	L							238	1641		245	1689	13	49	
	-110		194	T	260	1793	274	1889	9	32					
				ST	262	1806	274	1889	8	32					
				L	259	1786	274	1889	11	49					
	4½ by 13		114 by 330	Forging	Aged at 950° F (783 K) for 3 hr	Room	Room	ST	243	1675	255	1758	8	35	
								L	243	1675	255	1758	10	46	
								-110	194	ST	265	1827	276	1903	7
	L		266	1834	280	1930	10			44					
	4½ by 4½		114 by 114	Forging	Aged at 950° F (783 K) for 3 hr	Room	Room			T	248	1710	256	1765	7
								L	247	1703	258	1779	13	56	
		-110						194	T	272	1875	281	1937	8	35
	L		273	1882	281	1937	10		49						
	1½ by 13		38 by 330	Rolled plate	Aged at 950° F (783 K) for 3 hr	Room	Room		T	247	1703	258	1779	7	25
		L						244	1682	255	1758	10	43		
		-110						194	T	267	1841	279	1924	3	14
	L		262	1806	276	1903	8		30						
	1/2 by 13		13 by 330	Rolled plate	Aged at 950° F (783 K) for 3 hr	Room	Room		T	241	1662	252	1737	11	50
		L						244	1682	253	1744	11	54		
		-110				194	T	264	1820	275	1896	12	48		
							L	261	1800	273	1882	12	52		

^aT, transverse; ST, short transverse; and L, longitudinal.

TABLE V. - Concluded. SMOOTH TENSILE PROPERTIES FOR VARIOUS PRODUCT FORMS

[Average of two tests.]

Alloy	Melting practice	Cross-sectional size		Form	Condition	Test temperature		Test direction	0.2-Percent yield strength		Tensile strength		Elonga- tion, percent	Reduc- tion in area, percent						
		in.	mm			°F	K		ksi	MN/m ²	ksi	MN/m ²								
															(a)					
Maraging 250	Double- vacuum melt	13 by 13	330 by 330	Forging	Aged at 950° F (783 K) for 3 hr	Room	Room	T	243	1675	254	1751	6	14						
								ST	243	1675	255	1758	4	10						
								L	242	1668	255	1758	12	51						
						-110	194	T	265	1827	279	1924	4	12						
								ST	263	1813	277	1910	3	7						
								L	266	1834	280	1930	11	44						
		4½ by 4½	114 by 114	Forging	Aged at 950° F (783 K) for 3 hr	Room	Room	T	246	1696	256	1765	8	25						
								L	247	1703	258	1779	13	56						
								-110	194	T	273	1882	283	1951	5	22				
						L	269			1855	281	1937	11	54						
						9Ni-4Co-30	Vacuum-arc remelt			4½ by 4½	114 by 114	Forging	Tempered at 1000° F (811 K) for 2 hr	Room	Room	T	197	1358	228	1572
								L	202							1393	232	1600	19	65
-110	194	T	228	1572	251			1730	14							59				
		L	223	1538	252			1737	18					59						
		300M	Vacuum-arc remelt	4½ by 4½	114 by 114			Forging	Tempered at 575° F (575 K) 2 + 2 hr					Room	Room	T	241	1662	295	2034
L	243															1675	296	2041	12	34
PH 13-8Mo	Double- vacuum melt					13 by 13	330 by 330			Forging	Tempered at 1000° F (811 K) for 4 hr	Room	Room			T	204	1406	210	1448
														ST	200	1379	205	1413	14	58
														L	205	1413	212	1462	14	60
												-110	194	T	218	1503	230	1586	16	51
		ST	216	1489	230			1586	15					50						
		L	224	1544	234			1613	15					56						
		4½ by 4½	114 by 114	Forging	Tempered at 1000° F (811 K) for 4 hr	Room	Room	T	210	1448	218	1503	14	55						
								L	206	1420	214	1475	14	55						
								-110	194	T	227	1565	234	1613	13	47				
						L	229			1579	235	1620	14	53						
						1½ by 13	38 by 330			Forging	Tempered at 1000° F (811 K) for 4 hr	Room	Room	T	204	1406	212	1462	16	61
								L	202					1393	208	1434	14	60		
-110	194	T	226	1558	234			1613	14					58						
		L	219	1510	227			1565	16			58								
		Ti - 6Al- 6V-2Sn	Vacuum-arc melt	4½ by 4½	114 by 114			Forging	Aged at 1050° F (839 K) for 4 hr			Room	Room	T	154	1062	164	1131	8	18
L	149													1027	159	1096	13	21		
-110	194					T	184			1269	197			1358	9	20				
						L	181			1248	188	1296	8	16						
						1½ by 13	38 by 330			Rolled plate	Aged at 1050° F (839 K) for 4 hr	Room	Room	T	168	1158	176	1213	12	36
L	165													1138	172	1186	11	34		
-110	194			T	195			1344	202					1393	9	26				
				L	195			1344	200			1379	9	30						
				1/2 by 13	13 by 330			Rolled plate	Aged at 1050° F (839 K) for 4 hr			Room	Room	T	177	1220	181	1248	13	27
L	177													1220	181	1248	14	34		
-110	194					T	208			1434	211			1455	10	26				
						L	210			1448	212	1462	11	28						

^aT, transverse; ST, short transverse; and L, longitudinal.

TABLE VI. - INFLUENCE OF CROSS-SECTIONAL POSITION ON ROOM-TEMPERATURE SMOOTH TENSILE PROPERTIES OF FORGINGS

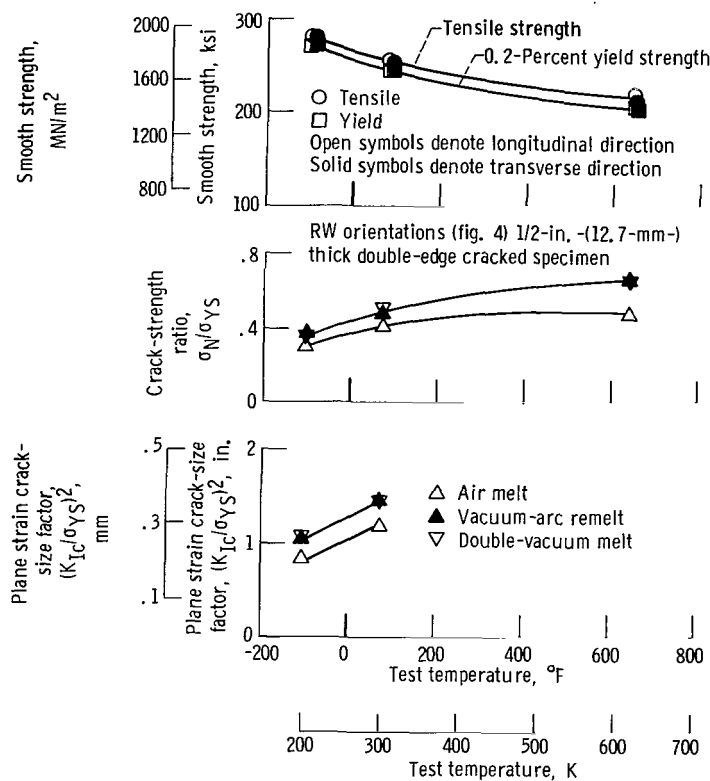
[Average of two tests; see table IV for 9Ni-4Co-30 steel.]

Alloy	Melting practice	Cross-sectional size		Aging treatment	Location	Test direction	0.2-Percent yield strength		Tensile strength		Elongation, percent	Reduction in area, percent
		in.	mm				(a)	ksi	MN/m ²	ksi	MN/m ²	
Maraging 250	Air melt	13 by 13	330 by 330	950 ⁰ F (783 K) for 3 hr	Surface	ST	237	1634	247	1703	9	30
					Mid-radius	ST	233	1606	246	1696	3	6
					Center	ST	233	1606	244	1682	3	4
Maraging 250	Vacuum-arc remelt	13 by 13	330 by 330	950 ⁰ F (783 K) for 3 hr	Surface	ST	234	1613	247	1703	9	37
					Mid-radius	ST	239	1648	250	1724	9	38
					Center	ST	236	1627	250	1724	7	34
Maraging 250	Double-vacuum melt	13 by 13	330 by 330	950 ⁰ F (783 K) for 3 hr	Surface	ST	242	1668	256	1765	3	11
					Mid-radius	ST	243	1675	255	1758	4	10
					Center	ST	241	1662	255	1758	3	10
PH 13-8Mo	Double-vacuum melt	13 by 13	330 by 330	1000 ⁰ F (811 K) for 4 hr	Surface	ST	196	1351	205	1413	17	57
					Mid-radius	ST	200	1379	205	1413	14	58
					Center	ST	189	1303	203	1400	18	58
Ti - 6Al-6V-2Sn	Vacuum-arc melt	4½ by 4½	114 by 114	1050 ⁰ F (839 K) for 4 hr	Surface	T	160	1103	168	1158	10	13
					Mid-radius	T	154	1062	164	1131	8	18
					Center	T	144	993	157	1082	10	23

^aST, short transverse; and T, transverse.

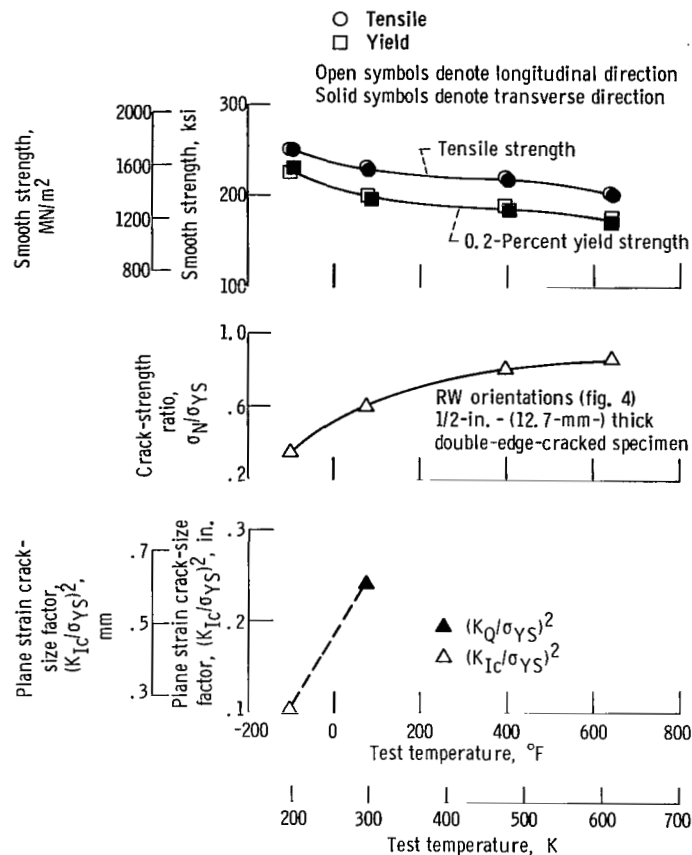
Effect of Temperature on Fracture Properties

The smooth tensile strength, crack- to yield-strength ratio σ_N/σ_{YS} , and the plane strain crack-size factor are shown in figure 6 as a function of test temperature for tests on the $4\frac{1}{2}$ - by $4\frac{1}{2}$ -inch (114- by 114-mm) forgings. As might be expected, the crack-strength ratio and the plane strain crack-size factor decrease with decreasing temperature. However, the way in which the embrittling effect of temperature develops and its magnitude are quite different for the various alloys tested. The PH 13-8Mo steel (fig 6(c))



(a) Maraging 250 grade steel.

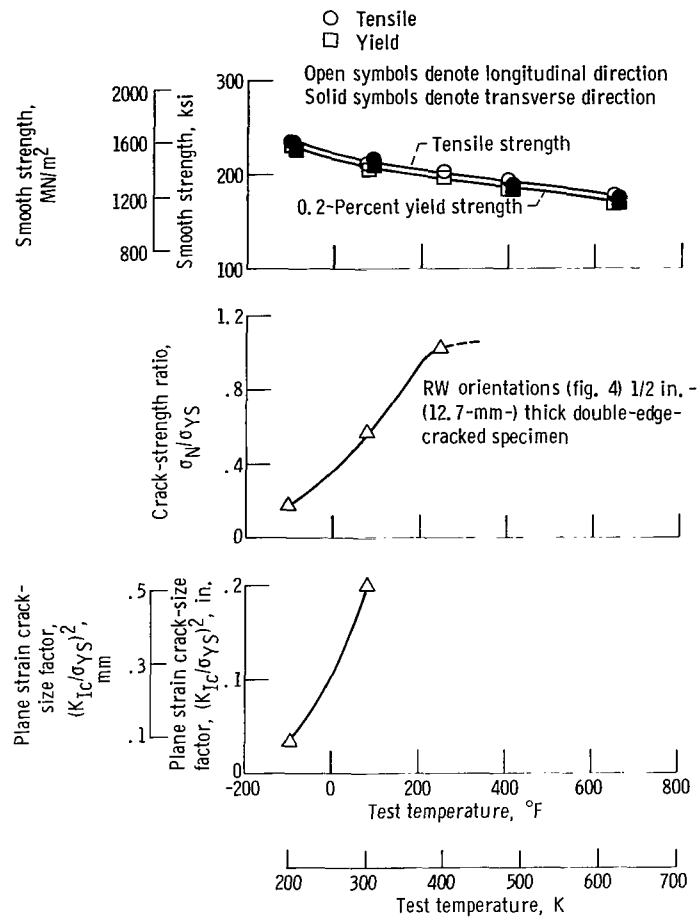
Figure 6. - Smooth tensile and crack strength properties as function of test temperature for $4\frac{1}{2}$ - by $4\frac{1}{2}$ -inch (114- by 114-mm) forgings. (Points shown are average of two or more tests.)



(b) 9Ni-4Co-30 steel.

Figure 6. - Continued.

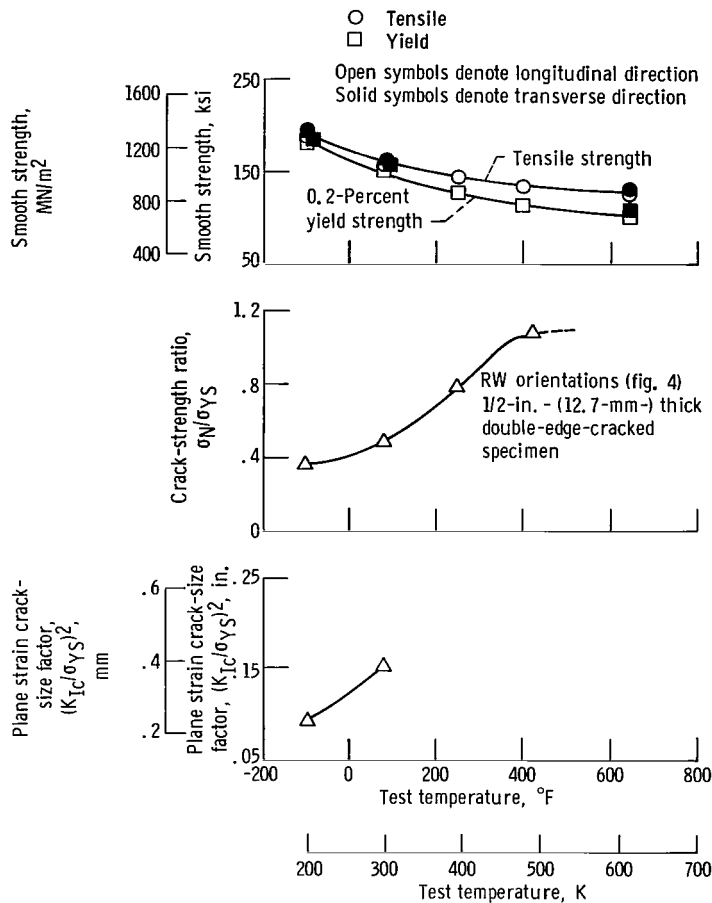
exhibits a rapid decrease in both crack-strength ratio and crack-size factor at temperatures below about 200° F (366 K), and is quite brittle at -110° F (194 K). The titanium alloy (fig. 6(d)) exhibits a similar but less pronounced behavior below 400° F (477 K) and has a -110° F (194 K) crack-size factor considerably above that of the PH 13-8Mo steel. The 9Ni-4Co-30 steel (fig. 6(b)) and the maraging steels (fig. 6(a)) exhibit more moderate changes in fracture properties as a function of temperature. However, the trend of the data for the 9Ni-4Co-30 steel indicates that a substantial embrittlement has developed at -110° F (194 K).



(c) PH 13-8Mo steel.

Figure 6. - Continued.

It is interesting to note that the crack-strength ratio of PH 13-8Mo steel and the titanium alloy (fig. 6(d)) is 1 or above at temperatures in excess of 400°F (477 K). In contrast, the crack-strength ratio of the maraging (fig. 6(a)) and 9Ni-4Co-30 steels is below 1 over the entire temperature range investigated. The trends of the crack-strength ratio above room temperature for the alloys investigated are primarily associated with mixed-mode fracturing and, as mentioned previously, do not necessarily provide an index of plane strain crack propagation resistance. However, ratios of 1 or above do indicate very high toughness for the crack size and thickness tested.



(d) Ti - 6Al-6V-2Sn.

Figure 6. - Concluded.

Effects of Crack Orientation on Fracture Properties

Any effect of crack orientation on the -110° F (194 K) plane strain crack-size factor was within the scatter of the data for all product forms of the 9Ni-4Co-30, 300M, and PH 13-8Mo steels and for the titanium alloy forgings. However, as shown in table VII, crack orientation effects were observed for some product forms of the maraging steel and for the titanium alloy plate. This table gives an indication of the data scatter that was typical for all alloys tested at -110° F (194 K).

TABLE VII. - INFLUENCE OF CRACK ORIENTATION ON -110° F (194 K) FRACTURE PROPERTIES

OF VARIOUS PRODUCT FORMS^a

Alloy	Melting practice	Cross-sectional size		Form	Aging treatment	Test direction	Plane strain crack-size factor, $(K_{Ic}/\sigma_{YS})^2$							
		in.	mm											
							Individual tests (c)		Averages (d)					
		in.	mm				in.	mm	in.	mm				
Maraging 250	Air melt	13 by 13	330 by 330	Forging	950° F (783 K) for 3 hr	(b)	RT	(0.119)	(0.302)	0.071	0.180			
								.071	.180					
								RW	0.057			0.145	0.062	0.157
									(.070)			(.178)		
									.068			.173		
								WR	0.062			0.157	0.059	0.150
		.055	.140											
		WT	0.068	0.178	0.064	0.162								
			.060	.152										
			TW4	(0.060)			(0.152)	0.046	0.117					
				.053			.135							
				.040			.102							
			TW	0.059			0.175	0.060	0.152					
		.050		.127										
		4½ by 13	114 by 330	Forging	950° F (783 K) for 3 hr	(b)	RT	0.098	0.249	0.098	0.249			
								(.109)	(.277)					
								RW	0.086			0.218	0.086	0.218
									.085			.216		
									WR			0.071		
								.061				.155		
		WT	0.095	0.241	0.075	0.190								
			.073	.185										
			.058	.147										
			TW4	0.095			0.241	0.070	0.178					
.047	.119													
.068	.173													
TW	0.049	0.124	0.043	0.109										
	.036	.091												
4½ by 4½	114 by 114	Forging	950° F (783 K) for 3 hr	(b)	RT	0.090	0.229	0.092	0.234					
						(.103)	(.262)							
						RW	.095			.241	0.090	0.229		
							(0.120)			(0.305)				
							.093			.236				
						WR	0.072			0.183	0.073	0.185		
.065	.165													
WT	.081	.206	0.079	0.201										
	0.077	0.196												
	.064	.162												
	.097	.246												
	TW4	0.081			0.206	0.078	0.198							
		.074			.188									
TW	0.078	0.198	0.079	0.201										
	.080	.203												

^aUnless otherwise noted, values were obtained from single-edge-crack specimens.

^bFirst letter denotes direction of normal to crack plane; second letter denotes direction of crack propagation: R, rolling; W, width; T, thickness; TW4, 45° to a surface (see fig. 4).

^c K_{Ic} values in parenthesis.

^dAverages not reported for K_{Ic} values.

TABLE VII. - Continued. INFLUENCE OF CRACK ORIENTATION ON -110° F (194 K) FRACTURE

PROPERTIES OF VARIOUS PRODUCT FORMS^a

Alloy	Melting practice	Cross-sectional size		Form	Aging treatment	Test direction	Plane strain crack-size factor, $(K_{IC}/\sigma_{YS})^2$							
		in.	mm				in.	mm	in.	mm				
							Individual tests (c)		Averages (d)					
Maraging 250	Air melt	1½ by 13	38 by 330	Rolled plate	950 ^o F (783 K) for 3 hr	(b)								
						RT	0.077 .085	0.196 .216	0.081	0.206				
						RW	0.076 .069	0.175 .175	0.073	0.185				
						WR	0.069 .065	0.175 .165	0.067	0.170				
		WT	0.060 .065	0.152 .165	0.063	0.160								
		TW	^e 0.060 ^e .050	^e 0.152 ^e .127	0.055	0.140								
		1/2 by 13	13 by 330	Rolled plate	950 ^o F (783 K) for 3 hr	RW	(0.087) 0.073	(0.221) 0.185	0.073	0.185				
						WR	0.074 .068	0.188 .173	0.071	0.180				
Maraging 250	Vacuum-arc remelt					13 by 13	330 by 330	Forging	950 ^o F (783 K) for 3 hr	RT	(0.112) .099	(0.284) .251	0.099	0.251
										RW	(0.102) (.103)	(0.259) (.262)		
		WR	0.096 .090	0.244 .229	0.093					0.236				
		WT	(0.101) (.122) .093	(0.256) (.310) .236	0.093					0.236				
		TW4	0.074 (.116) .076	0.188 (.295) .193	0.076	0.193								
		TW	0.098 .097	0.249 .246	0.098	0.249								
		4½ by 13	114 by 330	Forging	950 ^o F (783 K) for 3 hr	RT	(0.117) (.119)	(0.297) (.302)						
						RW	(0.101) (.103)	(0.256) (.262)						
WR	0.097 (.103)					0.246 (.256)	0.097	0.246						
WT	(0.115) (.103)					(0.202) (.262)								
TW4	(0.105) (.104)	(0.267) (.264)												
TW	0.077 .075	0.196 .190	0.076	0.193										

^aUnless otherwise noted, values were obtained from single-edge-crack specimens.^bFirst letter denotes direction of normal to crack plane; second letter denotes direction of crack propagation: R, rolling; W, width; T, thickness; TW4, 45° to a surface (see fig. 4).^c K_Q values in parenthesis.^dAverages not reported for K_Q values.^eValues from 1/2-in. - (12.7-mm-) thick compact tension specimens.

TABLE VII. - Continued. INFLUENCE OF CRACK ORIENTATION ON -110° F (194 K) FRACTURE

PROPERTIES OF VARIOUS PRODUCT FORMS^a

Alloy	Melting practice	Cross-sectional size		Form	Aging treatment	Test direction	Plane strain crack-size factor, $(K_{Ic}/\sigma_{YS})^2$			
		in.	mm				in.	mm		
							Individual tests (c)		Averages (d)	
Maraging 250	Vacuum-arc remelt	$4\frac{1}{2}$ by $4\frac{1}{2}$	114 by 114	Forging	950° F (783 K) for 3 hr	RT	0.098 (.093)	0.249 (.236)	0.098	0.249
						RW	0.092 (.106) .091	0.234 (.269) .231	0.092	0.234
						WR	0.81 .91	0.206 .231	0.086	0.218
						WT	(0.104) .091	(0.264) .231	0.091	0.231
						TW4	(0.110) (.105) (.087)	(0.279) (.267) (.221)		
						TW	(0.114) (.108)	(0.290) (.274)		
		$1\frac{1}{2}$ by 13	38 by 330	Rolled plate	950° F (783 K) for 3 hr	RT	(0.105) .096	(0.267) .244	0.096	0.244
						RW	0.083 .094	0.211 .239	0.089	0.226
						WR	0.072 .080	0.183 .203	0.076	0.193
						WT	0.079 .095	0.201 .241	0.087	0.221
						TW	^e 0.061 ^e .071	^e 0.155 ^e .180	0.066	0.168
						RW	(0.110) (.102)	(0.279) (.259)		
$1/2$ by 13	13 by 330	Rolled plate	950° F (783 K) for 3 hr	WR	(0.104) .100	(0.264) .254	0.100	0.254		
				RT	0.085 .098	0.216 .249	0.093	0.236		
				RW	(0.105) (.106)	(0.267) (.269)				
				WR	0.073 .079	0.185 .201	0.076	0.193		
				WT	0.092 .085	0.234 .216	0.089	0.226		
				TW4	0.076 (.120) .087	0.193 (.305) .221	0.082	0.208		
13 by 13	330 by 330	Forging	950° F (783 K) for 3 hr	TW	0.074 (.105) .097	0.188 (.267) .246	0.086	0.218		

^aUnless otherwise noted, values were obtained from single-edge-crack specimens.^bFirst letter denotes direction of normal to crack plane; second letter denotes direction of crack propagation: R, rolling;

W, width; T, thickness; TW4, 45° to a surface (see fig. 4).

^c K_{Ic} values in parenthesis.^dAverages not reported for K_{Ic} values.^eValues from 1/2-in. - (12.7-mm-) thick compact tension specimens.

TABLE VII. - Concluded. INFLUENCE OF CRACK ORIENTATION ON -110° F (194 K) FRACTURE

PROPERTIES OF VARIOUS PRODUCT FORMS^a

Alloy	Melting practice	Cross-sectional size		Form	Aging treatment	Test direction	Plane strain crack-size factor, $(K_{Ic}/\sigma_{YS})^2$									
		in.	mm				in.	mm								
Maraging 250	Double-vacuum melt	$4\frac{1}{2}$ by $4\frac{1}{2}$	114 by 114	Forging	950° F (783 K) for 3 hr	(b)	Individual tests (c)		Averages (d)							
						RT	(0.114) (.120)	(0.290) (.305)								
						RW	(0.133) (.115) (.134)	(0.338) (.292) (.340)								
						WR	0.084 .085	0.213 .216	0.085	0.216						
						WT	0.080 .097	0.203 .246	0.089	0.226						
						TW4	0.093 .090	0.236 .229	0.092	0.234						
						TW	0.062 .078 .081	0.157 .198 .206	0.074	0.188						
						Ti - 6Al-6V-2Sn	Vacuum-arc remelt	$4\frac{1}{2}$ by $4\frac{1}{2}$	114 by 114	Forging	1050° F (839 K) for 4 hr	RT	0.090 .100	0.229 .254	0.095	0.241
												RW	0.079 (.118)	0.201 (.300)	0.079	0.201
												WR	0.076 .069	0.193 .175	0.072	0.183
WT	0.092 .093	0.234 .236	0.093	0.236												
TW4	0.079 (.118)	0.201 (.300)	0.079	0.201												
TW	0.082 (.102)	0.208 (.259)	0.082	0.208												
		$1\frac{1}{2}$ by 13	38 by 330	Rolled plate	1050° F (839 K) for 4 hr							RT	(0.044) .041 .048	(0.112) .104 .122	0.044	0.112
												RW	0.032 .029 .028 e.024 e.024	0.081 .074 .071 e.061 e.061	0.027	0.069
												WR	0.027 .028	0.069 .071	0.028	0.071
												WT	0.038 .032 .045	0.096 .081 .114	0.038	0.096
						TW	e.018 e.015	e.046 e.038	0.017	0.043						
								1/2 by 13	13 by 330	Rolled plate	1050° F (839 K) for 4 hr	RW	0.025 .024	0.064 .061	0.025	0.064
												WR	0.020 .021	0.051 .053	0.021	0.053

^aUnless otherwise noted, values were obtained from single-edge-crack specimens.^bFirst letter denotes direction of normal to crack plane; second letter denotes direction of crack propagation: R, rolling;

W, width; T, thickness; TW4, 45° to a surface (see fig. 4).

^c K_{Ic} values in parenthesis.^dAverages not reported for K_{Ic} values.^eValues from 1/2-inch- (12.7-mm-) thick compact tension specimens.

Forgings of square cross section might be expected to have a "rod" like rather than a "lamellar" like fiber structure, provided that a uniform degree of hot work was applied to adjacent faces of the forging. The degree of fibering should increase with decreasing cross section (increasing hot reduction). For this type of structure, the fracture properties might be expected to fall into two classes as a function of orientation depending on whether the cracks tend to cut through the rods or to split them. Thus, the RT and RW orientations should have the highest and nearly equal crack-size factors, while the other orientations should have lower but also approximately equal crack-size factors. Behavior following this pattern was observed for the $4\frac{1}{2}$ - by $4\frac{1}{2}$ -inch (114- by 114-mm) forging of air-melted maraging steel.¹ The vacuum-arc remelted maraging steel exhibited no clear directionality of fracture properties in the $4\frac{1}{2}$ - by $4\frac{1}{2}$ -inch (114- by 114-mm) forging. Nor were directionality effects evident for any of the 13- by 13-inch (330- by 330-mm) forgings of maraging steel, probably because the amount of hot work was not sufficient to develop the necessary degree of fibering.

Rolled plate might be expected to have a lamellar like structure so that the highest crack-size factors would be associated with the RT orientation and the lowest with the TW orientation.² Fracture behavior conforming to this type of structure was observed for the $1\frac{1}{2}$ -inch (38-mm) plates of air and vacuum-arc remelted maraging steel and the titanium alloy. The difference in fracture properties between the RT and TW orientations may be taken as an indication of the degree of fibering, and it will be noted that this difference is much greater for the titanium alloy than for the maraging steel.

The $4\frac{1}{2}$ - by 13-inch (114- by 330-mm) forgings of maraging steel received an unequal amount of hot work on the adjacent faces of the forging and therefore exhibited some of the directionality effects normally associated with plate. Thus, the RT orientation had the highest and the TW orientation the lowest fracture properties for the air melted material. While valid K_{Ic} values were not obtained for the RT orientation of the vacuum-arc remelt, the data do indicate a similar but smaller degree of directionality than for the air melt.

Effects of Section Size on Fracture Properties

The effects of fabricated section size on the plane strain crack-size factor are summarized in table VIII for the maraging 250 grade steel, the PH 13-8Mo steel, and the

¹Valid K_{Ic} values were not obtained for RT and RW orientations of the double-vacuum-melted maraging steel.

²The relation between the other crack orientations would depend in part on the degree of cross rolling which is unknown for the alloys investigated.

TABLE VIII. - EFFECTS OF FABRICATED SECTION SIZE ON -110° F (194 K) FRACTURE

PROPERTIES OF VARIOUS PRODUCT FORMS^a

Alloy	Melting practice	Aging treatment	Cross-sectional size		Plane strain crack-size factor, $(K_{Ic}/\sigma_{YS})^2$			
			in.	mm	in.	mm	in.	mm
			Test direction ^b					
			RW		WR			
Maraging 250	Air melt	950° F (783 K) for 3 hr	13 by 13	330 by 330	0.062	0.157	0.059	0.150
			4½ by 13	114 by 330	.086	.218	.066	.168
			4½ by 4½	114 by 114	.090	.229	.073	.185
			1½ by 13	38 by 330	.073	.185	.067	.170
			1/2 by 13	13 by 330	.073	.185	.071	.180
Maraging 250	Vacuum-arc remelt	950° F (783 K) for 3 hr	13 by 13	330 by 330	(c)	(c)	0.093	0.236
			4½ by 13	114 by 330	(c)	(c)	.097	.246
			4½ by 4½	114 by 114	0.092	0.234	.086	.218
			1½ by 13	38 by 330	.089	.226	.076	.193
			1/2 by 13	13 by 330	(c)	(c)	.100	.254
Maraging 250	Double-vacuum melt	950° F (783 K) for 3 hr	13 by 13	330 by 330	(c)	(c)	0.076	0.193
			4½ by 4½	114 by 114	(c)	(c)	.085	.216
PH 13-8Mo	Double-vacuum melt	1000° F (811 K) for 4 hr	13 by 13	330 by 330	0.057	0.145	0.065	0.165
			4½ by 4½	114 by 114	.035	.089	.033	.084
			1½ by 13	38 by 330	.046	.117	.043	.109
Ti - 6Al-6V-2Sn	Vacuum-arc remelt	1050° F (839 K) for 4 hr	4½ by 4½	114 by 114	0.079	0.201	0.072	0.183
			1½ by 13	38 by 330	.027	.069	.028	.071
			1/2 by 13	13 by 330	.025	.064	.021	.053

^aValues obtained from single-edge-crack tension specimens.^bFirst letter denotes direction of normal to crack plane; second letter denotes direction of crack propagation: R, rolling; W, width (see fig. 4).^cAverage not reported for K_Q values.

titanium alloy. These data represent the RW and WR crack orientations which could be tested in all section sizes.

With the exception of the titanium alloy, the effect of section size on the -110° F (194 K) crack-size factor is rather small and not necessarily correlated with changes in tensile reduction-in-area values. (Compared tables V and VIII.) For the titanium alloy, the crack-size factor decreases with decreasing section size. This effect is probably associated with an increase in the amount of retained (unstable) beta in the as-quenched product. This beta transforms on aging to produce an increase in yield strength and a reduced toughness. These hardenability effects overshadow any improvement in plane-strain fracture properties which might be associated with increased hot working. It is interesting to note that the tensile reduction-in-area values (see table V) are approximately equal for both titanium alloy plate products but lower for the $4\frac{1}{2}$ - by $4\frac{1}{2}$ -inch (114- by 114-mm) forging. This indicates that the fracture properties of smooth specimens can react differently to changes in metallurgical structure than do the fracture properties of cracked specimens.

COMPARISON OF ALLOYS

For comparison of the various alloys, in terms of their plane strain crack-size factors, the forgings are considered separately from the plate products since their fabrication history and resulting structure can be quite different. Comparisons on the basis of results from single heats, as in this investigation, should be approached with caution. It is possible that the heat to heat variation for one alloy could be larger than the difference between the single heats of different alloys. However, for an investigation of this kind, using many heats would be prohibitively expensive and time consuming. With these thoughts in mind, it is best to consider the comparative results as tentative and as part of a body of developing information on plane strain fracture properties of engineering materials.

Comparison of Forgings

The alloys are compared in figure 7, where the plane strain crack-size factor is plotted against the ratio of yield strength to density for the $4\frac{1}{2}$ - by $4\frac{1}{2}$ -inch (114- by 114-mm) forgings. These data, taken from figure 6, represent the RW crack orientation for tests at room temperature and 110° F (194 K). Room temperature data for the $4\frac{1}{2}$ - by $4\frac{1}{2}$ -inch (114- by 114-mm) forging of 300M has been added to this plot, as well as a

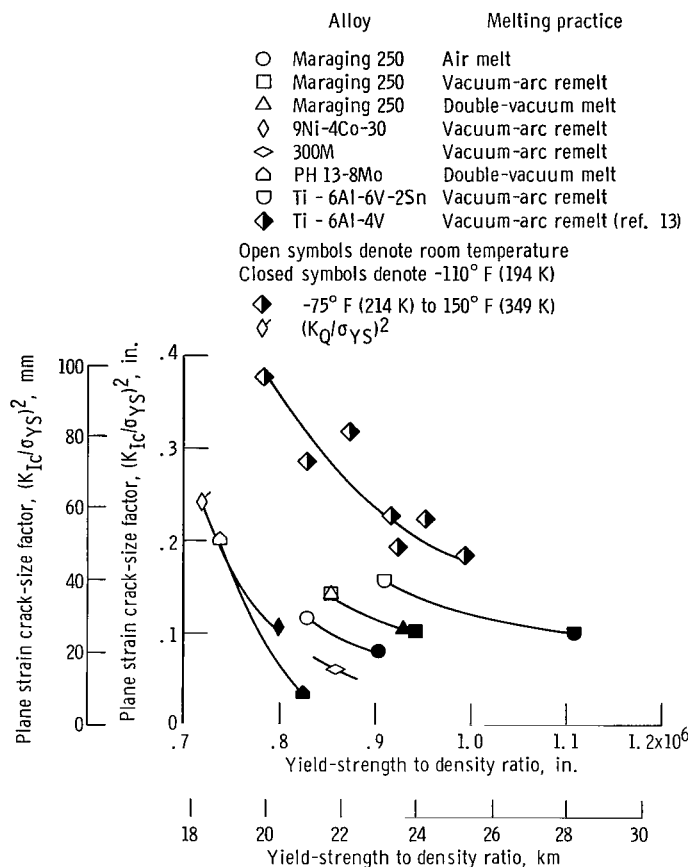


Figure 7. - Comparison of alloys on basis of plane strain crack-size factor for $4\frac{1}{2}$ - by $4\frac{1}{2}$ -inch (114- by 114-mm) forgings using double-edge-crack specimens (except for ref. 13 where compact tension specimens were used).

curve representing the fracture properties of 6Al-4V titanium alloy 3-inch- (76-mm-) thick forged plate in the solution treated and aged condition (ref. 13). This alloy is a competitor of 6Al-6V-2Sn for use in heavy sections. On the basis of these data, the titanium alloys clearly exhibit the highest crack-size factors. The PH 13-8Mo and 9Ni-4Co-30 steels show a rapid decrease in crack-size factor with increasing yield strength to density ratio. This behavior is a reflection of their relatively low K_{IC} values obtained at -110° F (194 K). It is interesting to note that the room temperature crack-size factor for the 300M steel is well below those for the other alloys.

Comparison of Rolled Plates

The fracture properties of the maraging steel and the titanium alloy, in the form of

$1\frac{1}{2}$ -inch (38-mm) and 1/2-inch (13-mm) rolled plate, are compared in table IX, which gives the yield-strength to density ratio and the plane strain crack-size factor at -110° F (194 K) for the RT, RW, WR, and TW crack orientations where applicable. In contrast to its behavior as a forging, the titanium alloy plate exhibits considerably lower crack-size factors than the maraging steel plate. This difference is associated with the higher yield strength to density of the titanium alloy. The low crack-size factor for the titanium alloy plate in the TW orientation is evidence for a strongly fibered structure.

Effect of Melting Practice on Maraging Steels

The results of several investigations (refs. 8 to 11) have established that the toughness of 18 Ni maraging steels, as measured by the Charpy V impact test, is increased by reduction in the residual element content. The content of residual elements may be reduced by selection of raw material combined with vacuum melting. For example, it was reported in reference 10 that maraging 250 grade steel produced with low sulfur raw material and induction-vacuum melted (carbon deoxidized and vacuum alloyed) had substantially higher Charpy V impact energy than conventional air melted material at the same yield strength level. While the improvements in Charpy V properties are undoubtedly worthwhile, it is not possible to derive from such data the corresponding effects on the K_{Ic} values.³

The results of the present investigation permit a comparison of three melting practices, namely, air melt, vacuum-arc remelt from the air melt, and a double-vacuum melt (induction-vacuum melt and alloy plus vacuum-arc remelt). Table X shows the fracture data corresponding to these three melting practices in the 13- by 13-inch (330- by 330-mm) forgings. The crack orientations selected are those expected to differ most in their fracture properties. According to table X, the -110° F (194 K) crack-size factors are essentially no different for the 13- by 13-inch (330- by 330-mm) forgings of the vacuum-arc remelted and the double-vacuum melted heats. For the air melted heat, the crack-size factor is distinctly lower than for the vacuum melts. For the $4\frac{1}{2}$ - by

³One investigation (ref. 12) obtained K_{Ic} data (using fatigue-cracked notch rounds) on 3-in. (76-mm) plate of 250 grade steel in the air melted and vacuum-arc remelted conditions. The vacuum-arc remelt was produced from the air melt, and an attempt was made to maintain the same fabrication history. The vacuum-arc remelted plate had significantly higher toughness values but the possible influence of vacuum melting was obscured by the higher yield strength of the air melted steel.

TABLE IX. - COMPARISON OF -110° F (194 K) FRACTURE PROPERTIES OF VARIOUS ALLOYS IN PLATE FORM^a

Alloy	Melting practice	Aging treatment	Cross-sectional size		Yield-strength to density ratio				Plane strain crack-size factor, $(K_{Ic}/\sigma_{YS})^2$											
					in.	km	in.	km												
			in.	mm					in.	mm	in.	mm	in.	mm	in.	mm				
					Test direction ^b															
					Transverse		Longitudinal										RT		RW	
Maraging 250	Air melt	950 ^o F (783 K) for 3 hr	1½ by 13	38 by 330	0.926×10 ⁶	23.5	0.926×10 ⁶	23.5	0.081	0.206	0.073	0.185	0.067	0.170	0.055	0.140				
			1/2 by 13	13 by 330	.940×10 ⁶	23.9	.946×10 ⁶	24.0	-----	-----	.073	.185	.071	.180	-----	-----				
Maraging 250	Vacuum-arc remelt	950 ^o F (783 K) for 3 hr	1½ by 13	38 by 330	0.923×10 ⁶	23.5	0.905×10 ⁶	23.0	0.096	0.244	0.089	0.226	0.076	0.193	0.066	0.168				
			1/2 by 13	13 by 330	.912×10 ⁶	23.2	.903×10 ⁶	23.0	-----	-----	(c)	(c)	.100	.254	-----	-----				
Ti - 6Al-6V-2Sn	Vacuum-arc remelt	1050 ^o F (839 K) for 4 hr	1½ by 13	38 by 330	1.190×10 ⁶	30.2	1.190×10 ⁶	30.2	0.044	0.112	0.027	0.069	0.028	0.071	0.017	0.043				
			1/2 by 13	13 by 330	1.270×10 ⁶	32.2	1.280×10 ⁶	32.5	-----	-----	.025	.064	.021	.053	-----	-----				

^aValues obtained from single-edge-crack tension specimens.

^bFirst letter denotes direction of normal to crack plane; second letter denotes direction of crack propagation: R, rolling; W, width; T, thickness (see fig. 4).

^cAverages not reported for K_Q values.

TABLE X. - COMPARISON OF -110° F (194 K) FRACTURE
 PROPERTIES^a OF MARAGING 250 GRADE STEEL FOR
 THREE MELTING PRACTICES

[Cross-sectional size, 13 by 13 in. (330 by 330 mm).]

Melting practice	Plane strain crack-size factor, $(K_{Ic}/\sigma_{YS})^2$					
	in.	mm	in.	mm	in.	mm
	Test direction ^b					
	RW		WR		TW	
Air melt	0.062	0.157	0.059	0.150	0.060	0.152
Vacuum-arc remelt	(c)	(c)	.093	.236	.098	.249
Double-vacuum melt	(c)	(c)	.076	.193	.086	.218

^aValues obtained from single-edge-crack tension specimens.

^bFirst letter denotes direction of normal to crack plane; second letter denotes direction of crack propagation: R, rolling; W, width; T, thickness (see fig. 4).

^cAverages not reported for K_Q values.

4½-inch (114- by 114-mm) forgings, the comparison is best made on the basis of results obtained with the 1/2-inch- (13-mm-) thick specimens, because valid K_{Ic} values were obtained for all three heats. These results, given in figure 6(a), also show the two vacuum melted heats to have essentially identical crack-size factors and the air melt to have lower values. However, it is interesting to note (see table VII) that only a rather small difference in crack-size factor between vacuum-arc remelt and air melt is observed for the TW orientation in 1½-inch (38-mm) plate.

While the data from this investigation of melting practice are too limited to draw firm conclusions, they do indicate that commercial vacuum-arc remelting of a conventionally produced maraging steel air melt can improve the plane strain crack propagation resistance. This improvement, however, was not clearly related to a reduction in residual element content. It will be noted from table II that the residual element content of all three heats was below the maximum values given in ASTM A538-65. While the air melt had the poorest fracture properties, its residual element content was essentially no different from that of the vacuum-arc remelt, except possibly for a higher silicon content.

PRACTICAL SIGNIFICANCE OF RESULTS

While the results of this investigation were obtained from single heats, it is possible to make a number of practical observations that should apply generally to the alloys investigated. When these observations are considered, it is important to remember that the fracture properties of weldments generally cannot be judged from the data on parent metal.

1. For the alloy conditions studied, significant loss in the plane strain crack-size factor can be expected as the temperature decreases from room to -110° F (194 K). This embrittlement is particularly pronounced for the PH 13-8Mo steel.

2. For critical applications in heavy forged sections, a potential improvement in fracture safety should be possible by substitution of maraging 250 grade steel or 6Al-6V-2Sn titanium for 300M steel.

3. For a particular alloy, the degree of anisotropy of fracture properties depended strongly on the product form with the least directionality being exhibited by the symmetrically worked forgings. As a consequence, the selection of an alloy for a particular application will depend on the product form.

4. Substantial variation in the center fracture properties with fabricated section size can be expected for the 6Al-6V-2Sn titanium alloy.

5. For maraging 250 grade steel, vacuum-arc melting appears to yield an improvement in the plane strain crack-size factor compared with air melting. Whether this improvement is tied to a reduction in residual element content it is not clear.

6. Substantial variations in the smooth bar reduction in area with changes in fabricated section size or with testing direction in forgings do not necessarily correspond to variations in the plane strain crack-size factor.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 16, 1968,
124-08-08-21-22.

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